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Review and analysis of the failure risk mitigation via monitoring for monopile offshore wind structures

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ABSTRACT

Structural health monitoring systems are gaining more attention in the offshore wind industry as they offer valuable insights into the integrity status of operating assets. Whilst most Class Society Rules and International Standards recognise the importance of implementing a condition-based maintenance strategy, they only provide theoretical guidance. Ultimately, it is the asset owner's responsibility to determine how to integrate this strategy into their broader operation and maintenance planning, including identifying which components to monitor and which monitoring techniques to employ. The present paper applies the Failure Mode, Effects, and Criticality methodology to identify the most critical failure modes to prioritise for monopile offshore wind structures. Hence, the potential benefits of incorporating structural health monitoring systems within a condition-based maintenance strategy and exploiting lifetime extension possibilities are assessed. To achieve this, a novel 4-step methodology is introduced, involving understanding failure mechanisms (time-dependent behaviour and pattern), current regime (inspections at intervals), monitoring options (both direct and indirect), improvement potential evaluation through 5 key performance indicators relevant for optimal O&M, which is more comprehensive and realistic than considering only monetary consequence of failure. The study addressed the prevailing failure modes in 5 categories, namely fatigue, corrosion, deformation, buckling and displacement, and connection failure, aiming to demonstrate potential improvement in terms of risk mitigation against these failure modes. The results of this study can significantly help offshore wind developers optimise where and how to allocate their resources for structural health monitoring, resulting in long-term cost reduction opportunities.

Abbreviations, Acronyms and Symbols

SHMS	Structural Health Monitoring Systems
CBM	Condition-based Maintenance
O&M	Operation and Maintenance
OWT	Offshore Wind Turbine
WTG	Wind Turbine Generator
WT	Wind Turbine
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
LCoE	Levelised Cost of Energy
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Mode, Effect, and Criticality Analysis
RDS-PP	Reference Designation System for Power Plants
RNA	Rotor Nacelle Assembly
MIC	Microbial Induced Corrosion
O&G	Oil and Gas
SCADA	Supervisory Control and Data Acquisition
KPI	Key Performance Indicators
NDT	Non-destructive Testing
RAMS	Risk Assessment Method Statement
ROV	Remotely Operated Underwater Vehicle
ACFM	Alternating Current Field Measurement
ICCP	Impressed Current Cathodic Protection
MP	Monopile
TP	Transition Piece
AE	Acoustic Emission
N/A	Not assessed or answered
UT	Ultrasonic Testing
ER	Electrical resistance

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AIS	Automatic Identification System
ER	Electrical resistance
ER	Electrical resistance
FTA	Fault Tree Analysis
LVDT	Linear Variable Differential Transducers
HAZID	Hazard Identification
DRA	Design Risk Assessments
CH_4	Methane
O_2	Dioxygen
H_2	Hydrogen
H_2S	Hydrogen sulphide
kW	Kilo Watt
MW	Mega Watt
GW	Giga Watt

1. Introduction

The offshore wind industry has come a long way since the development of the Vindeby wind farm in Denmark in 1991. For example, the Vindeby near-shore wind farm had only eleven offshore wind turbines (OWT) with a nameplate capacity of 495 kW overall. After three decades, the offshore wind industry has matured, and it targets moving further from the shore with more powerful OWTs, resulting in a total installed nameplate capacity of more than 57.6 GW globally. Further, for the upcoming years, ambitious targets to increase significantly the installed capacity are set up in Europe, the Americas, and Asia, reaching a total of 227.5 GW by 2030 with an astonishing expected annual growth rate of 18.7 % (World Forum Offshore Wind, 2022; IRENA, 2019). This remarkable progress of the offshore wind industry strongly indicates that it is poised to make a substantial impact on the global energy landscape and become an integral part of the solution for the energy trilemma (sustainability, affordability, and security).

The growth seen in the offshore wind industry can be attributed to cost reductions from stable energy policies, technology innovation, upscaling of wind turbines and support structures, serial fabrication, and eased financial mechanisms (Allen et al., 2018). Reducing Capital Expenditure (CAPEX) is crucial for maintaining the competitiveness of the offshore wind industry, and so is the efficiency and intelligent management of current and future assets. In this regard, it is worth noting that Operational Expenditure (OPEX) accounts for about 23 % of the Levelised Cost of Electricity (LCoE) (Ioannou et al., 2018), and in some countries like Germany (NORWEP, 2017), this percentage can go up to 42 %, which is a result of ensuring high availability by preventing production losses.

The reliability of OWTs depends not only on the turbine subsystem but also on the balance of the entire plant, encompassing support structures, inter-array and export cables, and substations; moreover, the performance of these subsystems and components could have knock-on effects on the OWTs' capacity to operate and maintain. For instance, the ReliaWind project (Wilkinson et al., 2011) reported a rate of 3 failures per year in the foundation system, which would impact the availability as well as constrain the expected lifetime. Hence, operation and maintenance activities are planned on the structural assets to avoid failure risk. So far, such remedial activities have traditionally been done by predetermined preventative maintenance and corrective actions upon detecting any failures. According to BVG Associates (BVG Associates, 2017), typically, 20 person-hours are spent in inspection visits on an annual basis for monopile OWT support structures. This number can go up to 60 person-hours for a jacket-type support structure based on predetermined inspection and maintenance intervals and scope prescribed in the applicable international standards and classification society rules.

For the offshore wind industry to remain competitive, project developers and asset owners must explore all available opportunities to lower LCoE. Structural health monitoring systems (SHMS) are common in large infrastructure projects but have yet to be widely adopted in the offshore wind industry. Integrating these systems into Operation and Maintenance (O&M) can result in higher operational efficiency, especially for the structural systems that potentially benefit from a condition-based maintenance strategy instead of preventative maintenance. As a result, a further LCOE reduction can be achieved (ORE Catapult, 2017). However, such systems come with an additional effort and cost, which will only be worth it, provided that the critical failure modes with adequate monitoring potential have been identified beforehand.

So far, the efforts have focused on the failure modes and their potential causes as well as the risk mitigation strategies via preventative maintenance strategy, which offers a limited chance of optimising O&M activities and lowering the current LCoE. Alternatively, the present study advocates that efficiency in monitoring options employed within a condition-based maintenance (CBM) strategy must be scrutinised rigorously for the time-dependent failure mechanisms that are more appropriate to be monitored within a CBM strategy. To achieve this, a novel 4-step methodology is introduced, involving understanding failure mechanisms (time-dependent behaviour and pattern), current regime (inspections at intervals), monitoring options (both direct and indirect), improvement potential evaluation through 5 key performance indicators (KPI) relevant for optimal O&M.

A novel element of the introduced methodology is the 5 KPIs considered to evaluate the potential of monitoring strategies, which is more comprehensive and realistic than the commonly used KPI – monetary consequence of failure. These KPIs not only evaluate the cost-efficiency of O&M by aiming for a reduction in inspection frequency and intensity (KPI 1–2) but also the long-term effectiveness of O&M (KPI 3–5). The introduction of these new KPIs promises a better-managed structural integrity of offshore wind structures.

The present study's unique approach offers an immediate impact on the industry as well as has a significant contribution to the literature. However, the study relies on industry expert elicitation to benchmark monitoring options, which is qualitative and can be subjective. Nonetheless, to address this limitation, a diverse range of stakeholders were involved in the workshops (developers, structural design consultancy, manufacturers, and academia with operational experience) to minimise the drawback of subjective assessments.

This paper builds upon the Failure Mode Effects and Criticality (FMECA) methodology reported by Scheu et al (Scheu et al., 2019)., which was developed within the European Union-funded research programme ROMEO under the call topic Low Carbon Energy LCE- 13–2016. Following the FMECA methodology, over twenty industry experts were elicited over the course of several workshops, resulting in identifying, prioritising and proposing pathways to mitigate critical risks for offshore wind turbines. Such collaborative work involving multiple stakeholders is quite unique because the study is based on documented failure modes with clear insights from industry and current best practices.

The following section presents a literature review concerning failure modes of OWT structures, operation and maintenance practices and risk prioritisation methodologies, followed by sections describing the applied methodology, presenting results, discussing these results, and lastly, giving concluding remarks, respectively.

2. Literature review

2.1. Offshore wind turbine structures: failure modes

According to the Reference Designation System for Power Plants (RDS-PP) (VGB-Standard RDS-PP, 2014; Cevasco et al., 2021; Wang et al., 2022), a typical tri-blade horizontal-axis OWT can be divided into three main subsystems: the Rotor Nacelle Assembly (RNA), substructure and foundation. For clarity, the substructure and foundation system are referred to as support structures, whose function is to provide sufficient load-bearing capacity to the OWT during the project's lifespan, withstanding the wind and wave-induced loads and specific marine environment conditions. Both systems must be designed to transfer loads safely from the OWT structure to the ground within permissible deformation limits.

Operation in offshore conditions is more challenging and adverse compared to onshore environments due to the harsh marine environment; consequently, the ways in which the offshore structure can fail have a wider variety. Martinez-Luengo and Kolios (Martinez-Luengo and Kolios, 2015) conducted a comprehensive review of the main technological failure modes that might occur during the operational life of an OWT, including those concerning the substructure and foundation systems. Several failure modes covering these systems were identified: loss of capacity due to cyclic loading, soil instability, scour, abnormal loading (earthquakes, typhoons, extreme weather conditions, etc.), fatigue and fracture, corrosion, and excessive fouling. The review identified most of the well-known failure modes, except for those related to structural connection failures (Schwedler et al., 2018). The present paper aims to contribute to the literature by also addressing this missing part of the existing literature regarding the main failure modes of monopile OWT structures.

2.1.1. Cyclic loading

An OWT is subjected to various environmental and mechanical loads, such as cyclic loading from the wind and waves and from the seabed, along with service loads from the turbine during operation, which will inevitably cause the structure to experience significant stresses and strains over the course of its service life (Amirafshari et al., 2021; Shittu et al., 2021). Monopile structures are no exception to this, especially when subjected to cyclic loading, as suggested by Bhattacharya (Bhattacharya, 2019), Arany et al (Arany et al., 2017). and Cui et al (Cui et al., 2023).

2.1.2. Soil stability

Monopiles are rigid piles, and the foundation collapse can occur if the soil around the pile fails; in this case, there would be rigid body movement and tilting of the overall structure (Bhattacharya, 2014). Furthermore, soil stability and degradation as a result of the dynamic response of monopile structures under cyclic loading has not been well understood yet, and the failures that occurred as a result of the steady accumulation of permanent displacements can enforce OWT to be ultimately shut down (Carswell et al., 2016). The soil consistency and strength should be such that sufficient load-bearing capacity can be provided to the OWT to withstand horizontal and vertical design loads throughout its lifetime.

2.1.3. Scour

Scour development around monopile structures is known to significantly impact the dynamic characteristics of a system. In this regard, Mayall et al (Mayall et al., 2018). argued that the scour phenomenon can reduce the strength and stiffness of the foundation, leading to a change in the natural frequency of the structure. Further, Liu and Yang (Liu and Yang, 2019) demonstrated that the horizontal displacement at the top of the tower and the maximum bending moment acting on the structural system constantly increases with scour depth. Thus, the effect of scour can be detrimental to OWT operation. A severe example of this was observed in Robbin Rigg in 2015, as scour led to the decommissioning of two OWTs due to exceeding service conditions for a safe operation (G+ Global Offshore Wind Health and Safety Organisation, 2017).

Scour protection can be installed reactively or post-construction to mitigate the effects of the observed scour around the structures as it has taken place in Scroby Sands, Robbin Rigg and Arklow Bank sites (Harris and Whitehouse, 2017). However, this was one of these instances that the cure can be worse than the disease; for instance, the flow interaction with the protection can cause edge scour or secondary scour in the seabed around the protection, leading to scour depths larger than in those cases with no scour protection installed (Guan et al., 2022). A robust design of the scour protection system is required to avoid sinking failure of the scour protection layers, such as those reported in Horns Rev 1 (Sumer and Nielsen, 2013).

2.1.4. Abnormal Loading

In addition to the above, even though it is a site-specific concern, the presence of ice shall also be accounted for in the design, as moving ice can induce significant and abnormal load cases (Fransson and Bergdahl, 2009). Shi et al (Shi et al., 2018). pointed out the coupling effect between ice-induced and aerodynamic loads and the dynamic responses under operational and parked conditions. In other areas where seismicity is present, such as China, Japan, and Taiwan, due attention must be paid to small and large-scale earthquakes (Yeter et al., 2020; De Risi et al., 2018) and typhoon/cyclone loading (Kato et al., 2023).

2.1.5. Fatigue and fracture

An OWT is exposed to cyclic aerodynamic and hydrodynamic loading as well as other types of loading specific to the offshore wind farm site, which makes it prone to fatigue damage over time (Glisic et al., 2017). The objective of the fatigue design of an OWT is to ensure a sufficient lifetime to withstand cyclic loading throughout its operational life. The predicted fatigue life forms the basis for the definition of inspection programmes during the fabrication stage and the operational life on a reliability basis (Igwemezie et al., 2019). However, changes in the boundary conditions or uncertainties underlying the fatigue design process, such as the first eigenfrequency, have a significant effect on resulting fatigue life, which has been illustrated by Ziegler et al (Ziegler et al., 2015, 2019)., Kallehave et al (Kallehave et al., 2015). and Yeter et al (Yeter et al., 2019a). OWTs are exposed to vibration-induced forces throughout their operational lives that may cause a catastrophic failure unless resonance is avoided by proper stiffness and frequency designs (Cevasco et al., 2022). To avoid the risk of resonance, OWT structures should be designed with the first-order natural frequencies away from the constant rational speed (1 P) and the rotor blade passing frequency (3 P).

Other types of vibration force are those induced by cross-wind and wave misalignment situations or wind turbulence, which are known to have a significant influence on the fatigue life of OWT structures. The phenomena are characterised by increased fatigue loads and a small amount of system damping with no contribution from aerodynamic damping. As part of the Offshore Wind Accelerator initiative (Fischer and Kühn, 2010), the Carbon Trust conducted a study on the effect of periods of operational non-availability. The study revealed that the lack of aerodynamic damping considerably affected the OWT structures' fatigue life and concluded that the total fatigue damage is highly dependent on the non-availability of the OWTs.

Ziegler and Muskulus (Ziegler and Muskulus, 2016) also argued that inspections at the fabrication stage are critical to rule out gross errors, which could severely limit the fatigue life of the structures once in operation. In fact, defects found during these inspections at Greater Gabbard led to a major arbitration process between the asset owners and the engineering, procurement, and construction (EPC) after 52 out of 140 transition pieces were found to be defective (Windpoweroffshore.com, 2019).

2.1.6. Corrosion

The marine environment and seawater presence pose a risk of corrosion to structural assets. Environmental conditions, such as waves, seawater spray and temperature cycles, are the key factors for the rate at which corrosion occurs. Further, corrosion occurs both on the internal and external sides of monopiles. On the external side, steel is in contact with open sea water, and the most critical zones for corrosion are the atmospheric zone, splash/tidal zone, submerged zone and mud zone (DNV, 2016a). As suggested by Klijnstra et al (Klijnstra et al., 2017)., the highest corrosion rate is usually observed in the splash zone or just below the water level for more stagnant water.

As far as the internal section is concerned, early offshore wind projects were designed with no corrosion protection for the internal surface, relying on air-water tightness (Black et al., 2015). However, issues with the sealing and airtightness have led to higher corrosion rates than expected and retrofit campaigns in some instances. The dissolved oxygen in seawater is rapidly consumed in a completely airtight structure, and the media turns anaerobic, which may lead to microbial activity in the sediments to generate H_2S, as reported in Teesside (ORE Catapult, 2016a). As a result, the encountered issue was a symptom of Microbial Induced Corrosion (MIC). The oxygen content inside the foundation might also change due to slow seawater ingress through leaks at the cable protection system seal or degraded grouted connections (Black et al., 2015). Issues with the pH at the inner compartment can lead to corrosion rate changes due to the depolarisation of cathodic steel in acidic environments. Corrosion can take many forms of degradation mechanisms; those involving local or pitting corrosion could severely compromise the structural integrity due to the risk of corrosion fatigue and accelerated crack growth (Ziegler et al., 2016; Adedipe et al., 2016; Mehmanparast et al., 2017).

Protective coatings can be subject to various failure modes, such as degradation, mechanical failure and blistering, which impedes their ability to protect the surface on which they have been applied. Protective coatings are known to fail in the offshore wind industry; for example, "Horns Rev" offshore wind farm is known to have suffered from a major coating failure of eighty wind turbine foundations, which manifested after only six months of operation, and "Alpha Ventus" offshore wind farm, too, had a premature coating degradation requiring a repair campaign more expensive than the entire onshore works (Windpoweroffshore.com, 2019). This has led to turning attention to revisiting the performance of protective coatings in the offshore wind industry, such as the comprehensive research given by Momber et al (Momber et al., 2015).

2.1.7. Biofouling

Another specific condition of the offshore environment is the presence of marine growth, both in the form of hard and soft growth, which can be attached to the structure (ORE Catapult, 2016b). Marine organisms generally colonise a structure soon after installation, but growth reaches an asymptotic a few years after. Marine growth adds weight by increasing member diameters and attracts hydrodynamic loads but has little effect on the dynamic response of the structure in the first natural frequencies, with just some higher effect on higher-order modes (Shi et al., 2012). The effect of drifting offshore aquacultures on monopile structures was studied by Klijnstra et al (Klijnstra et al., 2017)., and the increase in drag force was found to be minimal. Another adverse effect of marine growth is the potential impact on the performance of protective coating systems (Momber et al., 2015) and corrosion damage (Momber et al., 2015; Wang et al., 2023).

2.1.8. Connection failure

The offshore wind industry was able to transfer significant expertise from the Oil & Gas (O&G) industry in the area of cylindrical shaped connections. Grouted connections consist of a tube-to-tube connection where the annulus is infilled with a high-performance mortar. This was used to resolve the connection between monopiles and transition pieces in the offshore wind farms built in the early 90 s. During inspection and maintenance activities, vertical slippage was detected in several structures in Denmark, the United Kingdom and the Netherlands (Schaumann et al., 2010), with Egmond aan Zee as the first site with reported issues in 2009 (Wc, 2010). The slippage occurred due to the opening of a gap between grout and steel when subject to significant bending moments, pile slenderness and ovalisation, and therefore, failing to support the axial load of the OWT (Seo et al., 2017).

Due to the large number of failed grouted connections, two joint industry projects were initiated in the form of intense design reviews concluding the use of grouted conical connections and the incorporation of shear keys (Lotsberg, 2013). Apart from the modified grouted connection type, the offshore wind industry has recently geared towards using flange bolted connections to resolve the connection between the monopile and transition piece, similar to the connection with the OWT tower bottom (Madsen et al., 2017). The challenge comes with the need for large bolt dimensions and inherent issues related to lowering strength and the impact of the pretension force during operational performance (Schwedler et al., 2018).

In the present section, several critical failure modes are identified and discussed based on the available literature. These failure modes might have highly consequential effects or impact the operational performance, and they can be triggered by causes with different likelihood of occurrences. If the combination of consequence and likelihood indicates intolerable risk, practicable risk-reducing measures can be implemented within the scope of operation and maintenance practices.

2.2. Operation and maintenance (O&M) practices

Asset Integrity is defined as the ability of a system to perform its required function effectively and efficiently over a defined period of time whilst protecting health, safety and the environment. An OWT support structure is subjected to a range of degradation mechanisms described in Section 2.1 that could impair its integrity during its operational life. Structural safety must be ensured for a given timeframe, typically 20–30 years, through the design process by carefully evaluating load levels, site conditions and material strengths for various limit states (Jadali et al., 2021). However, there is a significant degree of uncertainty during this design process in relation to the environmental and actual site conditions, the operational performance, and the design models themselves, which could affect the system integrity and, in turn, availability (Yeter et al., 2019a; Luengo et al., 2019; Page et al., 2019; Horn et al., 2019; Yeter et al., 2019b; Walgern et al., 2023). In order to maximise these two indicators, any industrial system or plant, such as an OWT, will be subject throughout its operational life to preventative and corrective maintenance activities as described in British Standards (British Standards, 2017) (see Fig. 1).

Typically, the integrity of OWT support structures is ensured by undertaking periodical inspections at predetermined time intervals, known as predetermined maintenance, and combining this with corrective maintenance activities in the form of event-driven inspections or repair activities. The latter can be triggered in the event of accelerated deterioration and degradation of the system or following an incident or event which may have compromised its integrity. These maintenance practices are addressed by offshore wind industry international standards, classification society rules and national state regulations such as IEC (IEC, 2018), DNV (DNV, 2016b), ABS (ABS, 2020), ClassNK (ClassNK), Bureau Veritas (Bureau Veritas, 2016), Lloyd's Register (Lloyd's Register, 2019), and BSH (BSH BfSuH, 2015). Due to the commonalities between O&G platforms and OWT support structures, the associated O&M regimes can be somehow deemed similar and transferable. This is the reason why asset owners can refer to O&G standards to supplement the aforementioned offshore wind industry-specific regulations, namely ISO (ISO IOfS, 2020) and API (API, 2020).

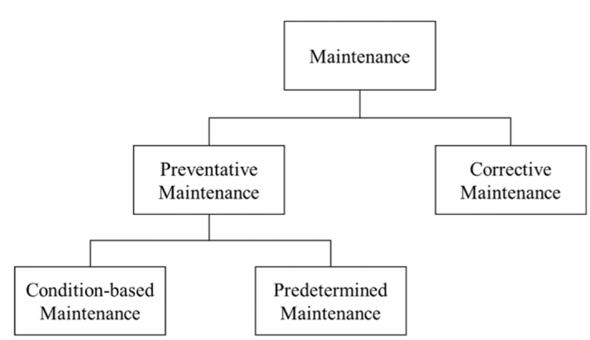

Fig. 1. Maintenance types (British Standards, 2017).

The alternative to predetermined maintenance is known as Condition-based Maintenance (CBM). British Standards (British Standards, 2017) defines CBM as a type of preventative maintenance that includes a combination of condition monitoring, inspection, testing, analysis and subsequent maintenance actions. Crucially, in a CBM strategy, the condition of systems or components is monitored in order to determine a dynamic preventive schedule (Márquez et al., 2018) based on "symptoms of failure" (ISO IOfS, 2018; Pandit et al., 2023). The CBM strategy is gaining importance in the offshore wind sector due to the increasing level of competitiveness in the industry, the need to lower the operational expenditure (OPEX) and thus efficient and cost-effective maintenance strategies.

The first publications on O&M optimisation through CBM strategies in the wind industry date back to the 1990 s, yet it was following the WT-OMEGA project (Verbruggen, 2003) that the first state-of-the-art review of monitoring techniques for the detection of developing faults in mechanical systems was presented. As a successor of the WT-OMEGA project, the CONMOW project addressed the use of direct and indirect measurement techniques for fault detection, including real-site applications for offshore wind farms (Wiggelinkhuizen et al., 2008).

The consideration of offshore wind farms got increased attention since then, with relevant papers produced by Sørensen (Sørensen, 2009) incorporating for the first time the factor of risk, and Nielsen and Sørensen (Nielsen and Sørensen, 2011) focused on the potential cost savings by moving away from a corrective maintenance approach to a CBM strategy. Since then, several papers have been produced focusing on optimised O&M strategies through risk and condition-based approaches, the use of SCADA and other signals for predictive maintenance and the condition monitoring techniques suitable for early fault detection in mechanical and electrical OWT components (McKinnon et al., 2022).

It was not until Rolfes et al (Rolfes et al., 2009). addressed the topic of condition monitoring in the form of SHMS for the substructure and foundation systems in an OWT as a method to optimise the O&M regime. Since then, several papers have been published addressing the opportunity of introducing condition monitoring techniques to assess the actual consumed fatigue life of the structures, detect the appearance of degradation mechanisms and support asset management decision-making (Weijtjens et al., 2015; Iliopoulos et al., 2016; Weijtjens et al., 2017; Bouty et al., 2017; Tewolde et al., 2017; Dong et al., 2018; Ren et al., 2021; Rinaldi et al., 2021; Yeter and Garbatov, 2022; Kolios, 2022). All studies concurred that a continuously monitored fatigue life and structural integrity level could serve an important role in deciding over wind farm inspections, repowering or lifetime extension.

The potential benefits of incorporating SHMS within the overall O&M strategy for OWTs include reduced inspection costs and preventive maintenance, increased system availability and lifetime extension. These have been recognised by the vast majority of applicable norms for OWT structures by making explicit reference to the acceptance of CBM as an O&M strategy. Table 1 provides an overview of the acceptable operation and maintenance practices for OWT structures based on relevant international standards, classification society rules, and national state regulations.

Despite the general acceptance of CBM strategies by the regulatory paradigm, this topic is only addressed theoretically, with a general lack of practical guidance. Therefore, it is commonly left up to the asset owner's discretion to incorporate a condition-based maintenance strategy in the overall O&M scheme for the OWT structures and select the corresponding monitoring techniques, namely SHMS.

2.3. Failure risk and monitoring prioritisation

The present paper does not intend to provide an in-depth review of the available monitoring techniques for implementation in OWT structures, as several papers are already available in the literature providing comprehensive reviews on this topic. To name the most relevant, Wymore et al (Wymore et al., 2015). reviewed those monitoring techniques of primary application to the wind industry in general; Currie et al (Currie et al., 2013). focused on onshore foundations; Martinez-Luengo et al (Martinez-Luengo et al., 2016). discussed extensively SHMS implementation for offshore wind turbines; and recently, Yeter et al (Yeter et al., 2022). addressed the artificial intelligence support on the SHMS and lifetime extension of offshore wind assets. However, all concluded that the importance of SHMS depends very much on how specific monitoring techniques are selected in a justified manner to tackle a set of specific objectives of the CBM strategy.

However, this approach fails to account for a potential improvement that monitoring one or more specific systems can offer for the ongoing O&M regimes. The rationale of risk and optimisation opportunities can be applied to aid this prioritisation process.

However, there are only a few publications available to date that present a systematic approach towards prioritising monitoring

Table 1
Review of international standards, class society rules and national regulations applying to OWT structures and their requirements for the operational phase.

Norm	Organisation	Type	Scope	Year	Operation and maintenance		
					Predetermined maintenance	Condition-based maintenance	SHMS Guidance
IEC 61400–3	International Electrotechnical Commission	International Standard	Offshore wind	2018	Not specified	Not specified	Not specified
DNV-ST-0126	Det Norske Veritas	Class Society Rule	Offshore wind	2016	Yes	Yes	Not specified
ABS#176	American Bureau of Shipping	Class Society Rule	Offshore wind	2020	Yes	Yes (*)	Not specified
ClassNK	Nippon Kaiji Kyokai	Class Society Rule	Offshore wind	2014	Yes	No	Not specified
BV-WFPC-100	Bureau Veritas	Class Society Rule	Offshore wind	2016	Yes	Yes	Not specified
LR - Guidance Notes	Lloyd's Register	Class Society Rule	Offshore wind	2018	Yes	No	Not specified
BSH 7005	Federal Maritime and Hydrographic Agency	National State Regulation (Germany)	Offshore wind	2015	Yes	Yes	Yes (**)
EN ISO 19902	International Organization for Standardization	International Standard	Offshore structure (Generic)	2020	Yes	Yes	Not specified
API RP 2A-WSD	American Petroleum Institute	International Standard	Offshore structure (Generic)	2020	Yes	Yes	Not specified

(*) Selection of only specific locations for inspection is not permitted (sample-based inspection).
(**) In the former version, the standard requirement was to have 10 % of representative OWT structures equipped with SHMS. SHMS may be required through 'Single Case Approval' and application of 'Observation Method'.

techniques for OWT, including structural systems. In this regard, Shafiee and Dinmohammadi (Shafiee and Dinmohammadi, 2014) presented an integrated FMEA (Failure Mode Effect Analysis) and risk-based methodology for prioritising onshore and offshore wind turbine systems for monitoring based on the economic impact as a consequence of a failure. Sixteen systems were evaluated, and particularities for onshore and offshore were ascertained when identifying probabilities and consequences of failure. With the proposed modified FMEA, the tower system, which included the foundation subsystem per the definitions considered, was ranked as the most critical wind turbine assembly with high failure vulnerability and cost of failure. For the blade subsystem, Lopez and Kolios (Lopez and Kolios, 2022) performed a thorough Failure Mode, Effect and Criticality Analysis (FMECA), qualifying maintenance strategies and allocating more mitigation resources to the most critical identified risks. Subsequently, Zhou et al (Zhou et al., 2015). applied the FMECA framework in an ontology representation to enable prioritising monitoring based on the risk profile of each wind turbine system assessed. However, the study was limited to small-scale onshore wind turbines, which do not represent the industry trend in OWT, and did not consider the structural subsystems.

It was not until Artigao et al (Artigao et al., 2018). that the monitoring prioritisation in the wind industry was addressed again. This study analysed and compared thirteen reliability studies to understand where work should be focused on condition monitoring design and development, covering forty wind turbine systems and subsystems for onshore and offshore sites. The study pointed out the importance given in the literature to the structural systems, such as the tower and foundation subsystem, referring to six (Wilkinson et al., 2011) and two reliability studies (Reder et al., 2016), respectively. Conversely to Shafiee and Dinmohammadi (Shafiee and Dinmohammadi, 2014), the structural subsystems were found to be the most reliable, with the lowest failure rates and associated downtimes.

An alternative approach is presented by Scheu et al (Scheu et al., 2019). in which failure modes for various OWT systems are prioritised following a series of FMECA workshops to then prioritise the systems based on their suitability and feasibility for incorporating condition monitoring systems. This research is contextualised within the European-funded ROMEO project and covered twelve FMECA workshops involving experts and leading companies from the offshore wind sector with an operational experience of more than 9 GW from over 2500 individual WTs.

The next section delineates the novel methodology introduced in this study, which involves understanding failure mechanisms (time-dependent behaviour and pattern), current regime (inspections at intervals), monitoring options (both direct and indirect), improvement potential evaluation through 5 key performance indicators (KPI) relevant for optimal O&M. The study pays due consideration to avoid making the cure (monitoring) worse than the disease “failure mode”. Therefore, one crucial aspect of this methodology is the rigorous examination of failure mechanisms so that reliable and applicable monitoring solutions can be engineered.

3. Methodology

This study builds upon the systematic FMECA process reported by Scheu et al (Scheu et al., 2019)., which was developed within the context of the ROMEO project. This section presents an in-depth review of shortlisted failure modes identified for monopile structures in relation to their monitoring potential to identify the most appropriate monitoring technologies for adopting a condition-based maintenance approach. A typical monopile layout and architecture were conceived as the basis for this study based on the structural categories and design framework defined by DNV (DNV, 2016b), as described in Table 2.

Failure mode identification and prioritisation for the support structures took place in the form of two FMECA workshops out of the twelve workshops on which the ROMEO project is based. The first workshop involved experts from leading offshore wind developers, reputed structural design consultancy firms, OWT manufacturers and academia with operational experience representing more than 70 % of the offshore wind capacity installed in Europe and involved in the design of more than 2400 OWT structures. Subsequently, a separate workshop was scheduled, but in this instance, it was tailor-made to investigate the physics behind common causes of failure and evaluate the capabilities of different monitoring techniques for timely identification of damages that could lead to failure, i.e., the loss of system integrity.

Table 2
Structural category and items of a monopile structure.

Structural Category	Item
Primary Steelwork	Monopile (MP)
	Transition Piece (TP)
	MP-TP Connection (grouted type)
	WT-TP connection (bolted type)
Secondary Steelwork	Access Systems
	J-tubes and Cables Interface
	Corrosion Protection Systems
	(Coating, external and internal Cathodic Protection)
Miscellaneous	Scour Protection / Seabed

This paper takes the outcome from the FMECA workshops and elaborates on the monitoring prioritisation activity conducted during the latter workshop for monopile structures. For each of the shortlisted failure modes, the following aspects were reviewed in-depth:

3.1. *Failure mechanism*

Review FMECA workshop sheets and extract relevant failure modes that passed the level of criticality set out in the quorum of the ROMEO project as being medium to high-risk category. An in-depth review of the failure mechanisms from root cause to failure mode was performed for each shortlisted failure mode, including in-between steps and the physics of the processes leading to failure. This led to selecting those failure mechanisms showing a time-dependent and/or degradation behaviour. As such, it is worth considering in a condition-based maintenance strategy – the specific time-dependent behaviour or pattern has been identified for each failure mode where applicable. Finally, failure modes were grouped by the nature of the failure mechanism and categorised based on their most likely root causes: fabrication, transport and installation (FT&I), design, and operation and maintenance (O&M).

3.1.1. *Current regime*

Review the current industry best practices in inspections in terms of their suitability to detect damages or signs of degradation in the support structure and/or items resulting from the materialisation of a specific failure mode. These inspections provide snapshots at planned intervals of the integrity status of the support structures, whereby the integrity throughout the operational life can be inferred and hence determine if they continue to comply with the design provisions and intent.

3.1.2. *Monitoring options*

Review currently available monitoring solutions, both direct and indirect, in terms of their applicability to address the shortlisted failure modes. This covers technologies already in use in the offshore wind industry as well as those which can be transferred from other industries, such as O&G and large infrastructure monitoring. Those failure modes, whose inherent characteristics made them unsuitable for monitoring or for which no monitoring solution exists yet is arguably available in the near future, were identified throughout the monitoring prioritisation process.

Improvement potential: Five Key Performance Indicators (KPIs) were defined to evaluate the benefits of incorporating one or more monitoring techniques to address each of the previously identified failure modes and associated degradation mechanisms. The KPIs below were set out to benchmark the current situation (see Table 3).

A score of 1 in any of the above-listed KPIs indicates that incorporating one or more monitoring techniques can contribute positively to satisfying the statement, i.e. a qualitative improvement compared to the as-today situation. Conversely, a score of 0 means that no improvement can be achieved by incorporating the given monitoring techniques. As a result, the improvement potential is measured on a scale from 0 to 5, resulting from the sum of the assigned score to all KPIs. If a monitoring technique does not improve in any aspect of the current situation, it would not warrant further consideration.

4. Results

4.1. Overview

109 failures related to the most common type of OWT support structure were identified through the FMECA workshops (Scheu et al., 2019). All failure modes related to monopile structures scoring within the medium or high-risk category were shortlisted and were subjected to monitoring prioritisation following the procedure outlined in Section 3. As a result, 33 failure modes were evaluated in-depth, and for 26 of them, a varying degree of improvement potential through monitoring was identified. Despite different failure modes with different causes and mechanisms, all could be classified into four categories: corrosion, fatigue, connection failure and deformation, buckling and displacement (shortened as “deform., buckling and disp.” in Fig. 2 and Fig. 3).

Fig. 2 summarises the monitoring potential per failure mode category for all the prioritised mechanisms. It is found that all those mechanisms leading to grouted connection failure have a clear optimisation potential through monitoring, whilst this is not so obvious for those leading to corrosion, as only about 40% of the prioritised mechanisms would benefit from monitoring. There are no suitable monitoring techniques for all identified failure modes and mechanisms, at least not in the current state of the art or with a suitable technology readiness level. For instance, issues concerning manufacturing or installation flaws are usually difficult to monitor; the same goes for one-off events during operations, leading to a certain failure mode.

Fig. 3 summarises the improvement potential per the KPIs defined in Section 3 for all failure mode categories and corresponding degradation mechanisms. It is found that those that can profit the most from a reduction in the frequency and scope of inspections are those often part of periodical inspections as defined in the relevant international standards, class society rules and national regulations (Table 1). This is of high significance for those related to corrosion, which scores the highest in KPI 1 and KPI 2. In most cases, it is possible to avoid secondary damages by early detection of developing failures (KPI 5).

Specific patterns and medium to long-term degradation mechanisms are the most suitable for introducing a monitoring technique. This is the application for all failure mode categories but less so for bolted connection failure, which is less relevant due to the redundancy of this type of connection. Finally, early detection and monitoring of degradation mechanisms related to fatigue, grouted connection failure and deformation, buckling and displacement offer the largest opportunities for updating structural capacity (KPI 4), adjusting operations accordingly and exploiting any reserves for lifetime extension at the point of decommissioning.

Table 3
Key performance indicators set out for benchmark.

Identifier	Description
KPI 1	Reduction in the frequency of periodical inspections
KPI 2	Reduction in the extent/depth of periodical inspections
KPI 3	Possibility to defer and prevent corrective maintenance
KPI 4	Potential to update structural capacity and exploit reserves for lifetime extension
KPI 5	Opportunity to avoid secondary damages by early detection of failure mechanism

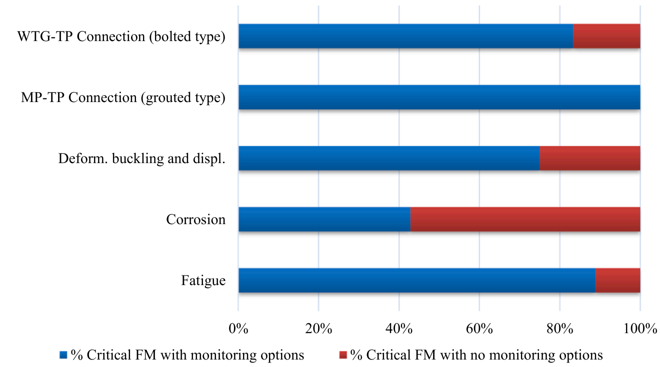

Fig. 2. Monitoring potential of critical failure modes for monopile OWT structures.

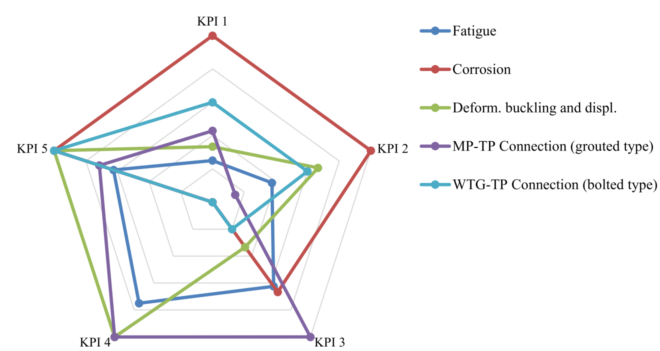

Fig. 3. Improvement potential per KPI and critical failure mode for monopile OWT structures.

Each failure mode category and the prioritised failure modes are described in the subsections below, covering details such as mechanism and failure path, current regime and practises, suitable monitoring techniques and optimisation potential. The areas that can be improved by considering monitoring techniques vary per failure mode.

4.2. Fatigue

Fatigue is one of the most relevant failure modes concerning OWT structures due to their dynamic behaviour and characteristic cyclic loading, which could translate into an early and/or accelerated consumption of the lifetime of the OWT structures beyond the provisions made during the design stage. Due to its significance, the analysis results in 9 failure modes having been prioritised. Various failure mechanisms can lead to fatigue, which is often materialised in crack initiation and propagation in welded joints and less commonly in parent steel material.

The failure paths leading to this failure mode can take the form of many physical degradation mechanisms or detectable behaviours. Table 4 presents the root cause, failure mechanism and current regime for monopile structure considering fatigue cracking. This turns into a wide range of available inspection and monitoring techniques suitable for the early detection of the mentioned degradation mechanisms leading to fatigue damage and the actual materialised damage (see Table 5).

4.3. Corrosion

Corrosion is the most common failure mode and degradation mechanism of any structure exposed to the harsh offshore environment, which could also work in tandem with other more advanced degradation mechanisms, such as cracking. Many inspection activities are planned

Table 4
Root Cause, failure mechanism and current regime for item “Monopile” considering failure mode “Fatigue”.

Root Cause	ID	Failure Mechanism / Path	Current Regime
Fabrication, Transportation & Installation	1.1.1	Not detecting an earlier crack initiation during inspections and crack growth/ propagation through cyclic loading	Surveillance and visual / NDT inspections at fabrication yards, transfer of custody and post-installation
	1.1.2	Contamination of the surface or insufficient surface preparation for coating, coating damage leading to corrosion	Surveillance and visual / NDT inspections at fabrication yards, transfer of custody and post-installation
	1.1.3	Excessive fatigue life consumption/loading during handling at the fabrication site, during shipping and installation	Surveillance and adherence to RAMS and lifting plans during the fabrication and installation stage
Design	1.2.1	Industry standards, e.g. material factor, SN curves not sufficiently applicable to wind, earlier crack initiation, and crack growth/propagation through cyclic loading	Subsea (ROV/diver) UT crack measurement, eddy current flaw detection or ACFM flaw detection, requiring marine growth removal prior to inspection
	1.2.2	With an internal ICCP system, the ventilation system is plugged, H_2 gas exceeds the allowed concentration, material becomes brittle, crack initiation and growth accelerated	Measurement of harmful gases prior to entering confined/ restricted access areas Measurement of hydrogen sulphide and hydrogen during drop-cell measurement
	1.2.3	Underestimation of wind turbine loads, environmental conditions and operational conditions, e.g. extreme events, grid faults	Indirect evaluation through above water and subsea (ROV/ diver) general and close visual inspection Reliance on the WTG alarm system
	1.2.4	Underestimation of marine growth	Subsea (ROV/diver) general visual inspection, thickness measurement through a probe or ACFM Fouling probe
Operation and Maintenance	1.3.1	With an internal/external ICCP system reference cell broken and gives wrong values, under-protection, corrosion	Drop-cell measurement from the working platform or contact/ proximity potential measurements with ROV/diver
	1.3.2	Scour protection damage, scour depth increased, degradation, excessive loading	Seabed surveys with multi-beam echo sounder and side scan sonar (vessel mounted, ROV or diver) Subsea (ROV/diver) general visual inspection or 3D laser imaging

regularly to evaluate the ambient conditions which can trigger more or less accelerated corrosion mechanisms and the performance of corrosion protection systems applied at the OWT structures. For a given offshore wind farm, it could be assumed that similar corrosion conditions and trends may affect the individual assets; hence, continuous monitoring could massively help optimise the inspection regime. The prevailing root cause, failure mechanism and current regime for the corrosion protection system are presented in Table 6, whilst Table 7 shows corresponding monitoring options and improvement potential.

Table 5
Monitoring options and improvement potential for item “Monopile” considering failure mode “Fatigue”.

ID	Monitoring Options	Improvement Potential Rating					
		1	2	3	4	5	Total
1.1.1	Acoustic emission (AE) and fatigue gauges	0	0	1	1	1	3
1.1.2	N/A	-	-	-	-	-	-
1.1.3	Strain gauges (electrical, optical) Ambient vibration monitoring	1	1	0	1	0	3
1.2.1	Acoustic emission (AE) and fatigue gauges	0	0	1	1	1	3
1.2.2	Hydrogen sulphide, hydrogen and other gas sensors	0	0	1	0	1	2
1.2.3	Strain gauges (electrical, optical) Ambient vibration monitoring	0	0	1	1	0	2
1.2.4	Indirectly through ambient vibration monitoring and modal analysis	1	1	0	1	0	3
1.3.1	Electrical resistance (ER) probe for real-time measurement of the corrosion rate Magnet-mounted reference electrodes measuring the protection potential	0	0	1	0	1	2
1.3.2	Pulse or radar devices (e.g. sonar mounted, Acoustic Doppler Current Profilers), optic fibre sensors, driven or buried rod devices (e.g. sliding magnetic collar), electrical conductivity, resistivity or capacity devices Indirectly through ambient vibration monitoring and modal analysis	0	1	0	1	1	3

Table 6
Root Cause, failure mechanism and current regime for item “Corrosion Protection System” considering failure mode “Corrosion”.

Root Cause	ID	Failure Mechanism / Path	Current Regime
Fabrication, Transportation & Installation	2.1.1	Coating system failure (peeling off, cracking, blistering, flaking, etc.)	Surveillance and visual / NDT inspections at fabrication yards, transfer of custody and post-installation
Design	2.2.1	Insufficient cathodic protection (electrical potential) in the internal and/or external section, e.g., excessive MIC	Drop-cell measurement from the working platform or contact/ proximity potential measurements with ROV/diver
	2.2.2	Acidification of internal compartment	Measurement of pH levels, temperature and dissolved oxygen during drop-cell measurement
	2.2.3	Build-up of gases like H_2S, H_2, O_2 or CH_4.	Measurement of harmful gases prior to entering confined/restricted access areas Measurement of hydrogen sulphide and hydrogen during drop-cell measurement
	2.2.4	Wrong anode location and interference	Indirectly through contact/proximity potential measurements, anode depletion assessment with ROV/ diver
Operation and Maintenance	2.3.1	Coating degradation through operational exposure	Above water and subsea (ROV/diver) general and close visual inspection
	2.3.2	Jet washing of marine growth attached to the structure	Above water and subsea (ROV/diver) general and close visual inspection

Table 7
Monitoring options and improvement potential for item “Corrosion Protection System” considering failure mode “Corrosion”.

ID	Monitoring Options	Improvement Potential Rating					
		1	2	3	4	5	Total
2.1.1	N/A	-	-	-	-	-	-
2.2.1	Electrical resistance (ER) probe for real-time measurement of the corrosion rate Magnet-mounted reference electrodes measuring the protection potential	1	1	0	0	1	3
2.2.2	pH sensors	1	1	1	0	1	4
2.2.3	Hydrogen sulphide, hydrogen and other gas sensors	1	1	1	0	1	4
2.2.4	N/A	-	-	-	-	-	-
2.3.1	N/A	-	-	-	-	-	-
2.3.2	N/A	-	-	-	-	-	-

4.4. Deformation, buckling and displacement

Major deformations are usually related to extreme situations and instances where the boundary conditions for which the structures have been designed have been significantly breached. These deformations could take many forms and are generally easily identifiable through visual evaluation and/or flagged up via the WTG alarm system, as documented in Table 8 or excessive scour, damage to scour protection, as in Table 10. They severely compromise offshore wind turbine’s structural integrity; hence, their very early detection is crucial to avoid other failures. The monitoring options and improvement potentials for items “monopile” and “Scour Protection/Seabed” are given in Table 9 and Table 11, respectively.

4.5. Structural connection failure

Major structural connections such as those between MP-TP and TP-WT of whatever typology are of key relevance for the global structural system stability and integrity. This is translated into numerous prioritised failure modes: 7 failure modes for grouted MP-TP connection and 6 failure modes for TP-WT bolted connection, as presented in Table 12 and Table 14, respectively.(Tables 13 and 14)

Table 13 and Table 15 present the implementation of monitoring in the first massively helps to understand the actual behaviour of the confined grout material in terms of any review of the structural capacity. This type of connection is generally "inspection-free", and as such, there are only limited opportunities to reduce the inspection effort. However, the opposite occurs in the case of the bolted connection, which is subject to extensive inspection and maintenance work during the operational life.

Table 8
Root Cause, failure mechanism and current regime for item “Monopile” considering failure mode “Deformation, buckling and displacement”.

Root Cause	ID	Failure Mechanism / Path	Current Regime
Design	3.2.1	Underestimation of environmental and operational conditions, resulting in excessive loading	Indirect evaluation through above water and subsea (ROV/diver) general and close visual inspection or UT mapping Reliance on the WTG alarm system
	3.2.2	Overestimation of soil capacity, excessive soil degradation and pile displacement rotation	Verticality and airgap checks during above-water general visual inspection
Operation and Maintenance	3.3.2	Accidental ship impact on steelwork	Identification through AIS vessel system with post-event above water and subsea (ROV/diver) general visual inspection

Table 9
Monitoring options and improvement potential item “Monopile” considering failure mode “Deformation, buckling and displacement”.

ID	Monitoring Options	Improvement Potential Rating					
		1	2	3	4	5	Total
3.2.1	Strain gauges (electrical, optical) Ambient vibration monitoring	0	0	1	1	1	3
3.2.2	Inclinometers and accelerometers Indirectly through ambient vibration monitoring and modal analysis	1	1	0	1	1	4
3.3.2	N/A	-	-	-	-	-	-

Table 10
Root Cause, failure mechanism and current regime for item “Scour Protection/Seabed” considering failure mode “Deformation, buckling and displacement”.

Root Cause	ID	Failure Mechanism / Path	Current Regime
Operation and Maintenance	3.3.1	Excessive scour, damage to scour protection, underestimation of environmental conditions	Seabed surveys with multi-beam echo sounder and side scan sonar (vessel mounted, ROV or diver) Subsea (ROV/diver) general visual inspection or 3D laser imaging

Table 11
Monitoring options and improvement potential item “Scour Protection/Seabed” considering failure mode “Deformation, buckling and displacement”.

ID	Monitoring Options	Improvement Potential Rating					
		1	2	3	4	5	Total
3.2.1	Strain gauges (electrical, optical)	0	0	1	1	1	3

5. Discussion

A systematic approach has been applied to prioritise failure modes associated with a generic monopile OWT structure to assess the potential of implementing a CBM strategy, improve the state-of-art O&M regime of this type of asset, and exploit potential lifetime extension opportunities. A comparison with other similar studies available in the public domain covering the OWT structural system is presented herein.

Few precedents exist in the literature where a primary focus has been given to the structural system, two of which are reported by Kang et al (Kang et al., 2019a, 2019b)., focusing on the floating offshore wind turbines where the structure plays a very significant role. This study applied Fault Tree Analysis (FTA) to identify the most critical events inducing a failure in the support structure system of Floating OWT, with 15 events having been identified. Bharatbhai (Bharatbhai, 2015) focused instead on a 5 MW OWT installed on a bottom-fixed structure; however, the structural system mainly referred to the tower assembly and nacelle structural areas without meaningful consideration to the foundation elements, leading to only 2 failure modes identified through an FMECA. Kougioumtzoglou and Lazakis (Kougioumtzoglou and Lazakis, 2015) combined FMECA and HAZID methods for identifying the most critical components of an OWT and the subsequent risk evaluation during various activities in the installation and operational phase, attending to personnel safety, environmental protection, asset integrity and device operation to serve as a basis for maintenance prioritisation. To this end, 8 failure modes related to the structural system were assessed. Dinmohammadi and Shafiee (Dinmohammadi and Shafiee,

Table 12
Root Cause, failure mechanism and current regime for item "MP-TP Connection (grouted type)" considering failure mode "Structural connection failure".

Root Cause	ID	Failure Mechanism / Path	Current Regime
Fabrication, Transportation & Installation	4.1.1	Failed grout seal, leakage/over-spilling, volume of grout insufficient, reduced capacity in connection, global dynamics change	Surveillance and adherence to grouting operation RAMS (overflow check, visual inspection of seal, etc.) during installation stage
	4.1.2	Loss of hard material, water ingress in porous material, sliding of grout against steel	Surveillance and adherence to grouting operation RAMS (overflow check, visual inspection of seal, etc.) during installation stage
	4.1.3	Improper thermal environment during installation/curing process, reduced capacity of grout, global dynamics change	Surveillance and adherence to grouting operation RAMS during the installation stage
	4.1.4	Eccentricity during installation caused reduced capacity at one side of the MP-TP connection, and global dynamics change	Surveillance and adherence to grouting operation RAMS during the installation stage
Design	4.2.1	Loss of hard material, water ingress in porous material, sliding of grout against steel	Subsea (ROV/diver) close visual inspection of the grout seal. Measurement of vertical displacement of TP with respect to MP from confined/restricted access areas
	4.2.2	Excessive loads and displacement, debonding/lack of contact between steel and grout, sliding	Measurement of vertical displacement of TP with respect to MP from confined/restricted access areas Above water / subsea UT mapping
Operation and Maintenance	4.3.1	Excessive loads on grouted connection, e.g., ship impact, local impact affecting the rest of the connection, cracking, reduced capacity	Indirect evaluation through above water and subsea (ROV/diver) general and close visual inspection or UT mapping Grout core samples (intrusive) Reliance on the WTG alarm system

2013) conducted a benchmark study comparing traditional and fuzzy-FMECA for OWT system risk and failure mode analysis. The structural system was addressed in this study, covering 4 failure modes. Interestingly, both approaches concluded that the structural system was the most critical.

All studies mentioned above have in common the consideration of the OWT structural system within the considered risk analysis framework. Generally, this system ranks relatively higher in the risk rating due to the significant exposure to the environment, harsh offshore conditions, and the severe consequences of failure. However, in no case is the structural system addressed to the level of detail covered in the present study, where just for one type of bottom-fixed foundation, 33 failure modes categorised in four large groups are investigated, neither for monitoring prioritisation purposes.

The monitoring options suggested and ranked by the experts reflect the best practices in the industry that have proven to be beneficial, which are well-documented in the literature as well. Nevertheless, these monitoring options still have shortcomings and/or room for improvement. The following discussion gives an overview of the most recent publication on these monitoring options, reporting the potential solutions for the existing shortcomings.

Table 14
Root Cause, failure mechanism and current regime for item "WTG-TP Connection (bolted type)" considering failure mode "Structural connection failure".

Root Cause	ID	Failure Mechanism / Path	Current Regime
Fabrication, Transportation & Installation	4.1.1	Poor lubrication, ineffective contact between bolt and nut, connection undone	Above water general and close visual inspection. Torque checks using torque wrench/bolt tension checks
	4.1.2	Improper bolting sequence, uneven stress distribution, stress concentration, overutilisation	Torque checks using torque wrench/bolt tension checks
	4.1.3	Missing washers, improper stress transferral, loosening of connection	Above water general and close visual inspection. Torque checks using torque wrench/bolt tension checks
Design	4.2.1	Poorly specified pretension force, loosening of connection at one bolt, more bolts to loosen	Above water general and close visual inspection. Torque checks using torque wrench/bolt tension checks
Operation and Maintenance	4.3.1	Insufficient sealing against water through grease caps, corrosion	Above water general and close visual inspection
	4.3.2	Internal climate control broken, high humidity, corrosive environment	Above water general and close visual inspection

Table 13
Monitoring options and improvement potential for item "MP-TP Connection (grouted type)" considering failure mode "Structural connection failure".

ID	Monitoring Options	Improvement Potential Rating					
		1	2	3	4	5	Total
4.1.1	Indirectly through ambient vibration monitoring and modal analysis	0	0	1	1	1	3
4.1.2	Vertical, horizontal and torsional Linear Variable Differential Transducers (LVDT) Indirectly through ambient vibration monitoring and modal analysis	1	1	1	1	1	5
4.1.3	Indirectly through ambient vibration monitoring and modal analysis	0	0	1	1	1	3
4.1.4	Indirectly through ambient vibration monitoring and modal analysis	0	0	1	1	1	3
4.2.1	Vertical, horizontal and torsional Linear Variable Differential Transducers (LVDT) Indirectly through ambient vibration monitoring and modal analysis	1	0	1	1	1	4
4.2.2	Vertical, horizontal and torsional Linear Variable Differential Transducers (LVDT). Indirectly through ambient vibration monitoring and modal analysis Acoustic emission (AE)	1	0	1	1	1	4
4.3.1	Strain gauges (electrical, optical) Ambient vibration monitoring	0	0	1	1	1	3

Strain gauges, both electrical and optical, have been employed for a very long time to monitor the high-cycle fatigue damage accumulation as well as the large displacement. A good example of this was reported by Ziegler et al (Ziegler et al., 2019). by extrapolating measured loads along monopiles using aero-hydro-elastic simulations and a regression

Table 15
Monitoring options and improvement potential for item "WTG-TP Connection (bolted type)" considering failure mode "Structural connection failure".

ID	Monitoring Options	Improvement Potential Rating					
		1	2	3	4	5	Total
4.1.1	Acoustoelastic effect sensors, piezoelectric active sensing or piezoelectric impedance sensors. Indirectly through ambient vibration monitoring and modal analysis – (difficult to ascertain changes)	1	1	0	0	1	3
4.1.2	Strain gauges (electrical, optical)	1	1	0	0	1	3
4.1.3	Acoustoelastic effect sensors, piezoelectric active sensing or piezoelectric impedance sensors. Indirectly through ambient vibration monitoring and modal analysis – (difficult to ascertain changes)	0	0	1	0	1	2
4.2.1	Acoustoelastic effect sensors, piezoelectric active sensing or piezoelectric impedance sensors Indirectly through ambient vibration monitoring and modal analysis – (difficult to ascertain changes)	1	1	0	0	1	3
4.3.1	N/A	-	-	-	-	-	-
4.3.2	Humidity sensors	0	0	0	0	1	1

algorithm, which was validated with the field data from operating OWTs. Alternatively, Hübler and Rolfes (Hübler and Rolfes, 2022) showed that simulation-based approaches can also be used for spatial and temporal extrapolations across all the hotspots in a monopile. Apart from the support structure, Weijtjens et al (Weijtjens et al., 2021). illustrated how to use in-situ monitoring data from MP-TP connections to derive coefficients of empirical load transfer function and calibrate the finite element (FE) model.

In addition to the well-accepted vibration-based embedded SHMS reviewed in (Yeter et al., 2022; Antoniadou et al., 2015; Beganovic and Söffker, 2016; Civera and Surace, 2022), the use of machine learning (ML) techniques has been more common to resolve some of the data availability and reliability issues, either physics-based (De N Santos et al., 2023) or data-driven (DN Santos et al., 2021). In addition, One of the biggest challenges is regarding monitoring is environmental noise, as clearly stated by Martinez-Luengo et al (Martinez-Luengo et al., 2016). and employing supervised and unsupervised machine learning techniques for pattern recognition and prediction model development might of great interest for the development of CBM strategies, especially for SHMS involving acoustic emission (Xu et al., 2019; Ahmad et al., 2023). Acoustic emission has particularly been proven to be useful for grouted connections, as illustrated by (Tziavos et al., 2020; Hüsken et al., 2021; Maetz et al., 2023)

Ambient vibration monitoring has consistently shown promising results in representing the dynamic characteristics of monopile structure throughout its service life. In this regard, Iliopoulos et al (Iliopoulos et al., 2016). confirmed that inaccessible fatigue-critical locations along the monopile can be monitored and assessed using the modal decomposition and expansion approach via the FE model. After the first year of Block Island Offshore Wind Farm's operation, several studies confirmed the structural instrumentation and monitoring using accelerometers, inclinometers, and strain gauges can be effectively used to monitor fatigue life (Hines et al., 2023), modal parameters (Song et al., 2023) and to update FE model (Moynihan et al., 2023).

Corrosion has also been identified as a critical failure mode by the experts, and the electrical resistance probe for real-time corrosion rate measurement has been suggested. In addition, the non-destructive ultrasound technique was shown to inform about the thickness loss due to corrosion by Thibbotuwa et al (Thibbotuwa et al., 2022). More in-depth reviews of the corrosion monitoring and prognostics, including corrosion fatigue life assessment for fixed-bottom OWTs, are given in (Brijder et al., 2022; Liu et al., 2022; Leng et al., 2023; Okenyi et al., 2024).

This study deals with the implementation of monitoring solutions to enhance the current state-of-art of the O&M of monopile structures. Aspects regarding the reduction of inspection costs and preventive maintenance, as well as increased system availability and lifetime extension, are tackled through the incorporation of monitoring. However, indeed, monitoring may not be the only possible way to achieve such objectives as, for instance, increasing predetermined maintenance may lead to similar results depending on the failure mode being assessed. To address this shortcoming, a cost study should follow the qualitative study from which a list of prioritised failure modes is derived. The cost-saving opportunities, cost of implementation, technology readiness and supply chain availability should be carefully assessed to ensure the most cost-effective solution is chosen.

The results presented in this study could be used as the basis for the establishment of a generic risk register from which operators can systematically derive monitoring requirements based on the company's priorities and, as such, create a unified approach over the entire windfarm portfolio and make the transfer of lessons learned more effective. This would ensure that monitoring solutions are consistent across the project's portfolio. For new development projects, good timing for undertaking such exercise would be as part of the Design Risk Assessment (DRA), which is often solely focused on the health, safety, and environment considerations by extending their scope. Based on the generic risk register, particular requirements for the specifics of each project can be drawn upon at the basic or front-end engineering design phase.

6. Conclusions

The present paper presented an in-depth review and analysis of critical failure modes identified for OWT monopile structures in relation to their monitoring potential. For each failure mode, a review of the current industry best practices was presented, which was then followed by an evaluation of the available monitoring techniques of application to the given failure modes in terms of the optimisation potential they could offer to O&M and integrity management practices.

A total of 109 failure modes were identified, 33 failure modes were shortlisted due to their criticality level, and finally, 26 were found to have room for optimisation following the incorporation of monitoring techniques. All analysed failure modes were grouped into four main categories: fatigue, corrosion, deformation, buckling and displacement, and structural connection failure, and showed a significant degree of improvement potential.

As the offshore wind industry continues to grow, new and more efficient ways of operating and maintaining current and future offshore wind farms must be conceived to ensure the industry's competitiveness. Currently, a significant focus is given to the investment part – CAPEX; however, the operational period – OPEX should not be forgotten, and all the life cycle should be accounted for during the development and design phase, where a large portion of strategic decisions are taken.

This is particularly relevant as lifetime extension and re-powering are gaining importance in the industry. Planning for the end at the beginning during the early project phases is expected to be a game-changer for the offshore wind industry, mainly as OWTs larger than 10 MW and, subsequently, larger support structures (e.g., very large monopiles) are conceived by developers from 2020 onwards.

The results of this study can offer an immediate impact on the industry. However, the study relies on industry expert elicitation to benchmark monitoring options, and at this stage, the new KPIs can only measured qualitatively. Therefore, future work will focus on developing KPIs further to be quantifiable, which will be followed by a comprehensive life-cycle cost analysis of these suggested monitoring options to fit this study's outcomes into a risk-based decision-making framework.

Author statement

All authors contributed to the study's conceptualisation, methodology development and investigation. The FMECA workshops were held in the context of the European-funded ROMEO project. The original draft of the manuscript was written by Lorena Tremps, and all authors reviewed and edited the previous versions of the manuscript. All authors read and approved the final manuscript.

CRediT authorship contribution statement

Athanasios Kolios: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. **Lorena Tremps:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft. **Baran Yeter:** Data curation, Investigation, Methodology, Validation, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data Availability

The data that has been used is confidential.

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